AlGaN/GaN HEMT Degradation under Electrical Stress

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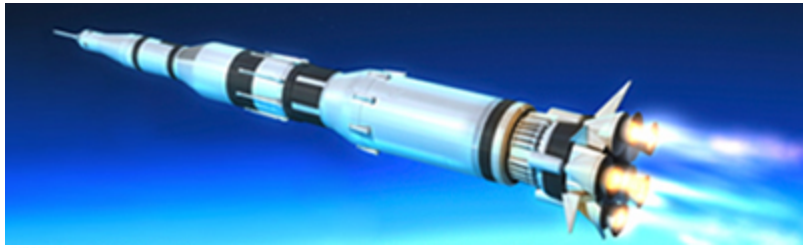
Outline

- Introduction
- High Power Stress
- Thermal Simulations
- Off-State Stress
- Conclusion

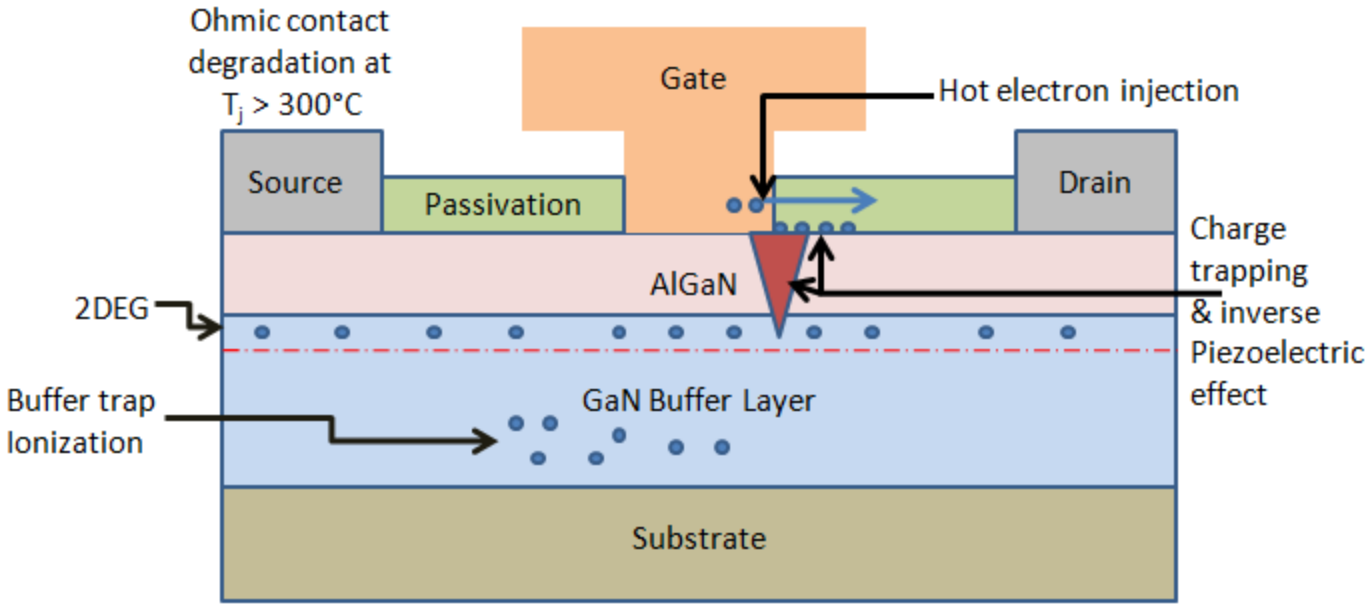
Introduction

- AlGaN/GaN HEMTs show exceptional promise for radar systems, high frequency & high power communications.
- MTTF > 10^6 hours at 200°C

  > 10^7 hours at lower temperatures
- Fundamental mechanisms due to electrical degradation still unknown.
- Need for understanding of mechanisms driving failure under standard operating conditions in the field.



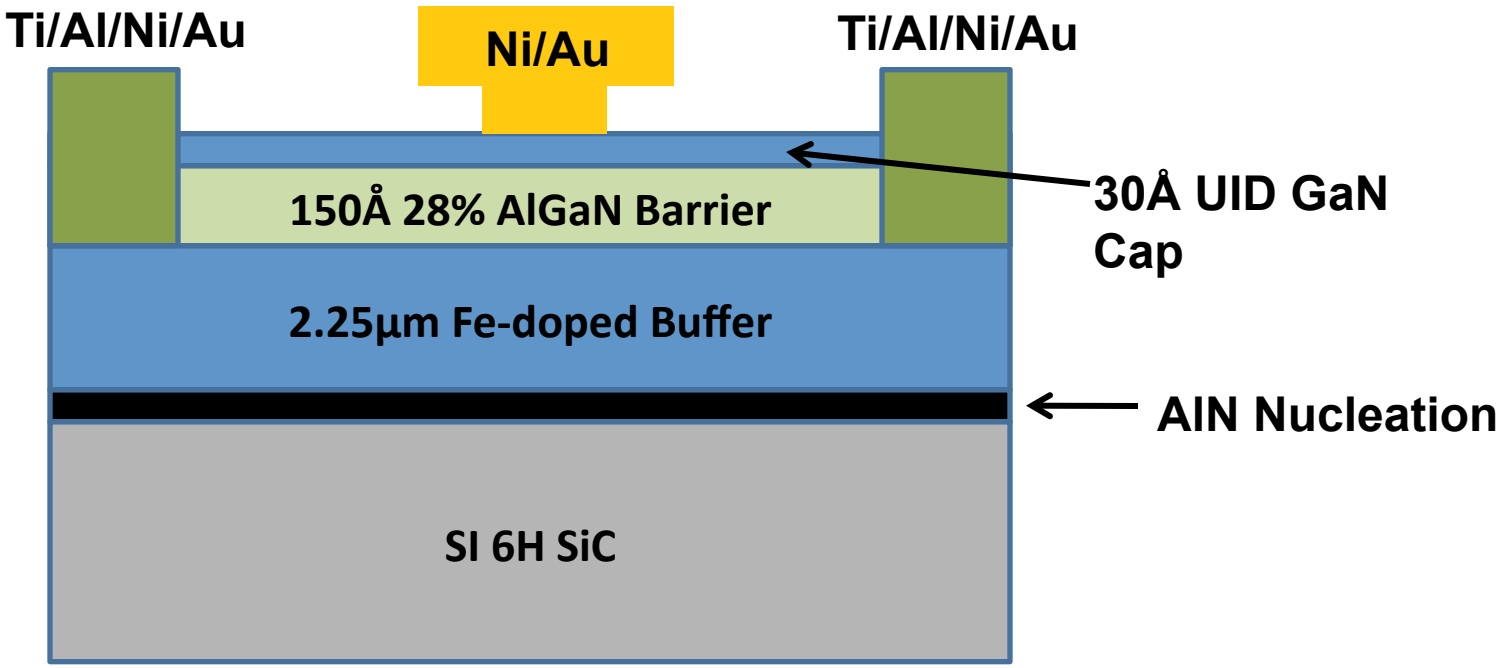
Introduction



Degradation Mechanisms:

1) Hot Electrons
2) Contact Degradation
3) Converse Piezoelectric Effect

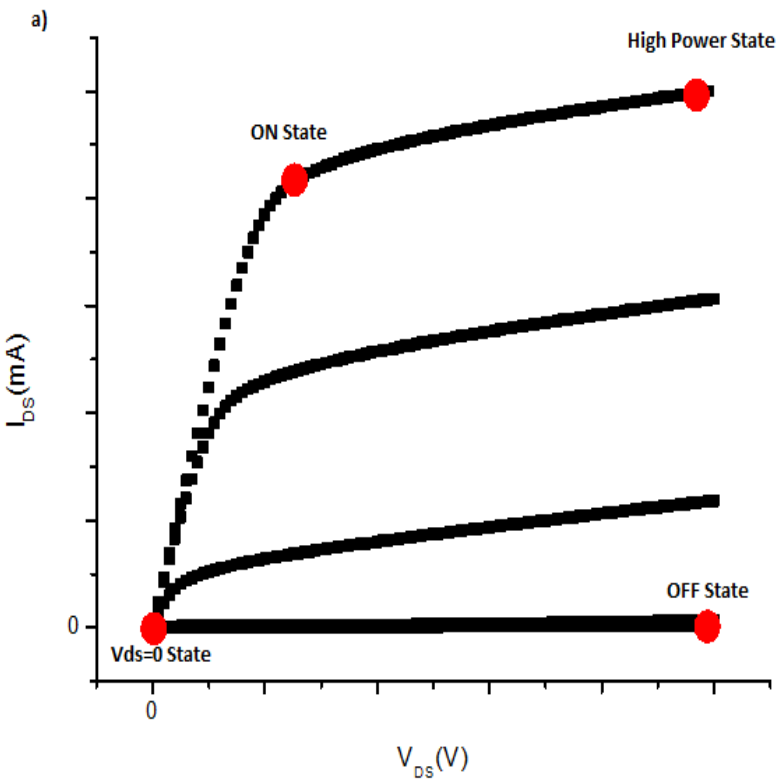
AFRL AlGaN/GaN HEMT

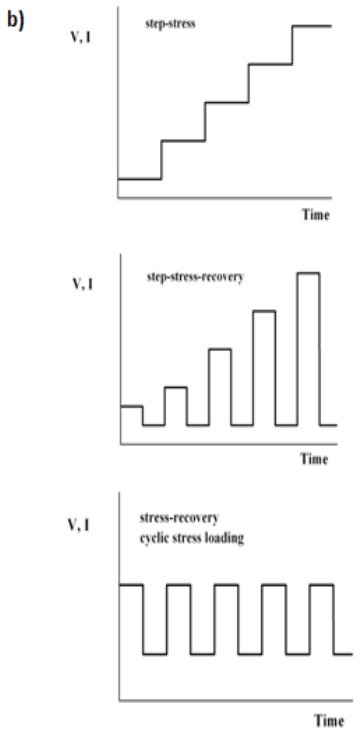


ICP mesa etch of ~1000Å
Ohmic contacts annealed at 850°C for 30 sec
Silicon nitride passivation

Degradation Experiments

Study effects of:
1) Current
2) Voltage
3) Temperature

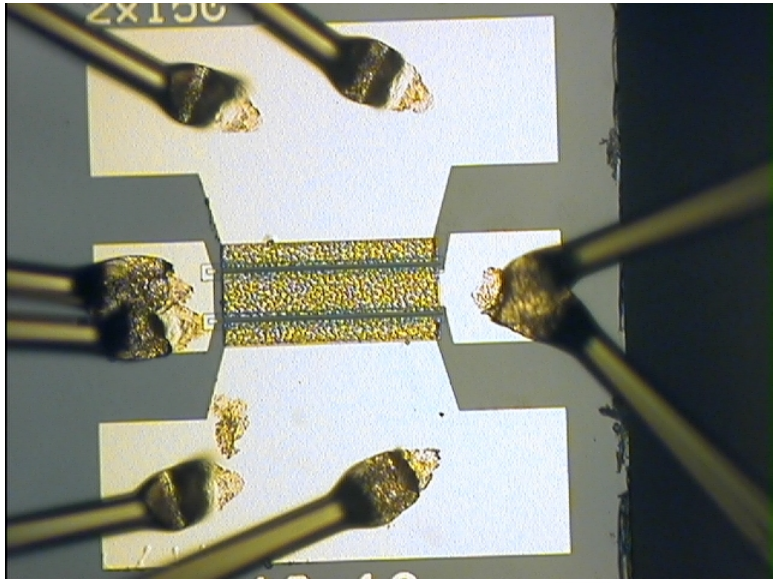


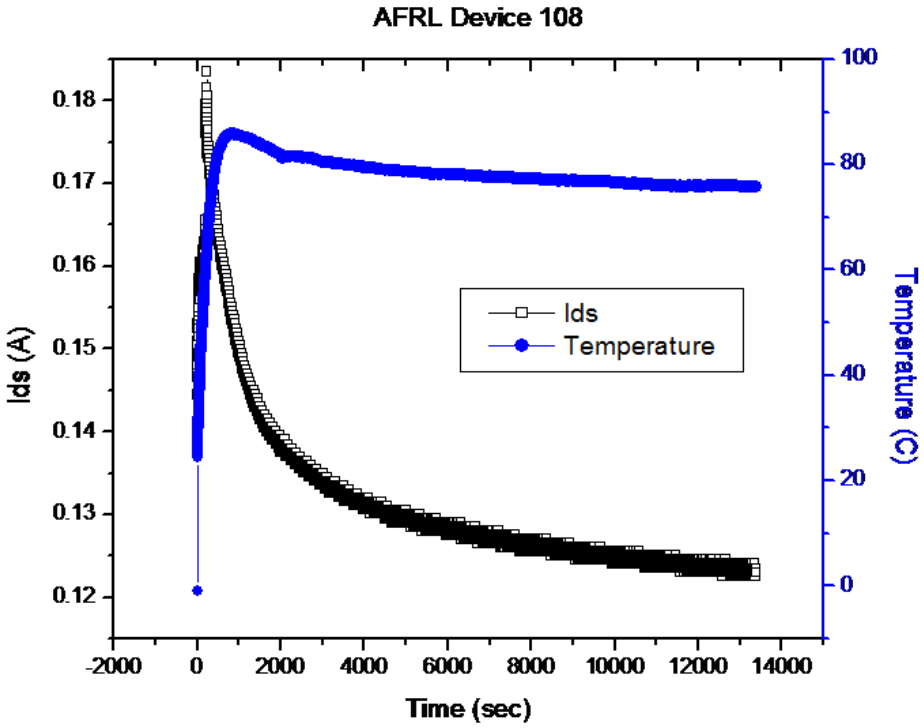


Initial Stress

Stressed 3 devices

- Failure criteria: -20% I_{DMax}
  - 2 devices failed within 3 minutes
  - 1 device survived almost 4 hours
- Noise measurements completed by Dr. Boseman's Group
- CL measurements done in order to pin-point areas of interest for TEM study



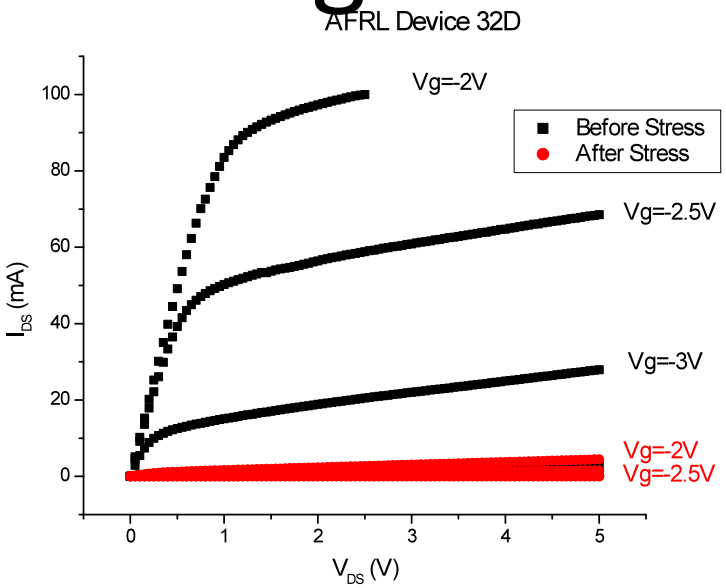


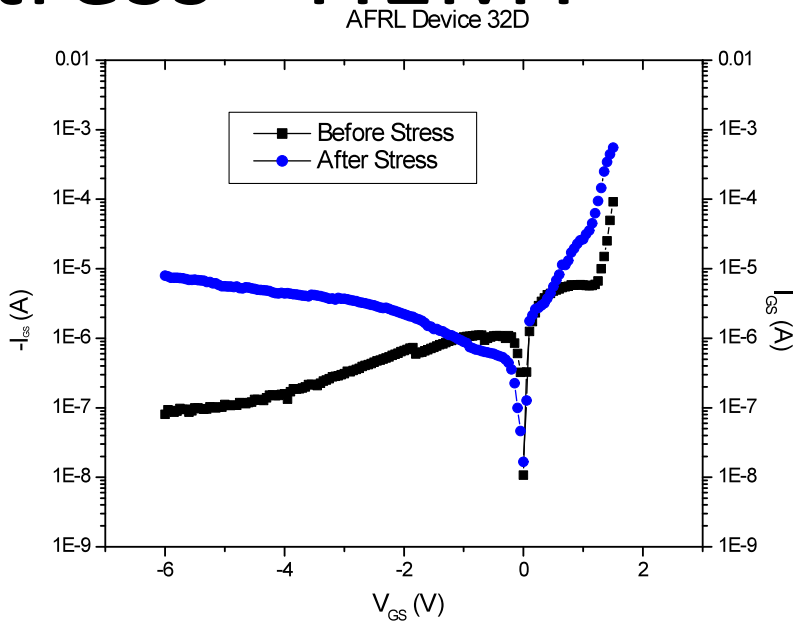
ON-State Stress Conditions

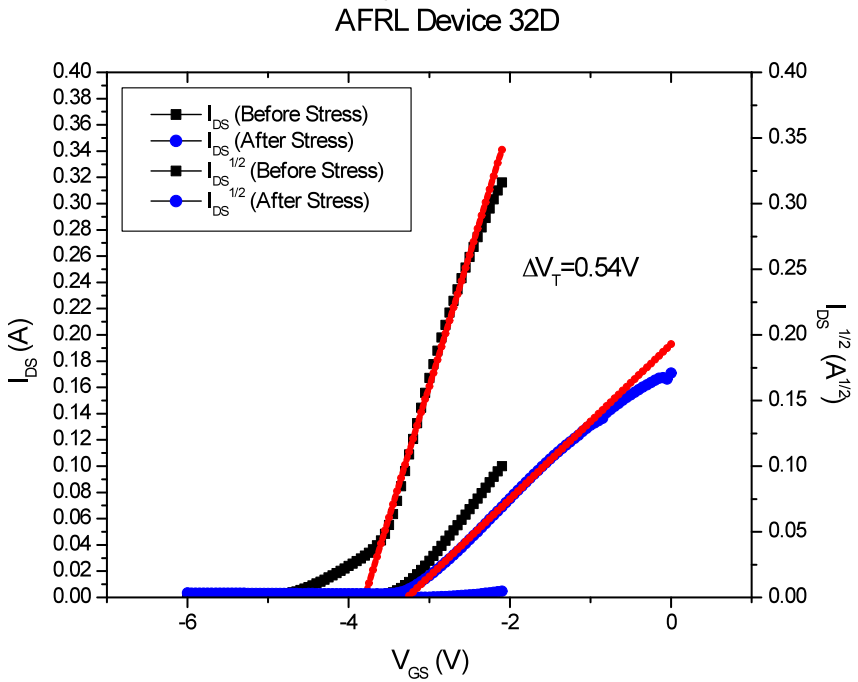
- V_{DS} stepped from 1-25V in 1V increments for 30 minutes intervals.
- Temperature controlled by peltier devices: 60°C, 80°C, and 100°C

    A. HEMT (4µm spacing)
    B. TLM with 5µm spacing
    C. Gateless (4µm spacing)

High Power Stress - HEMT





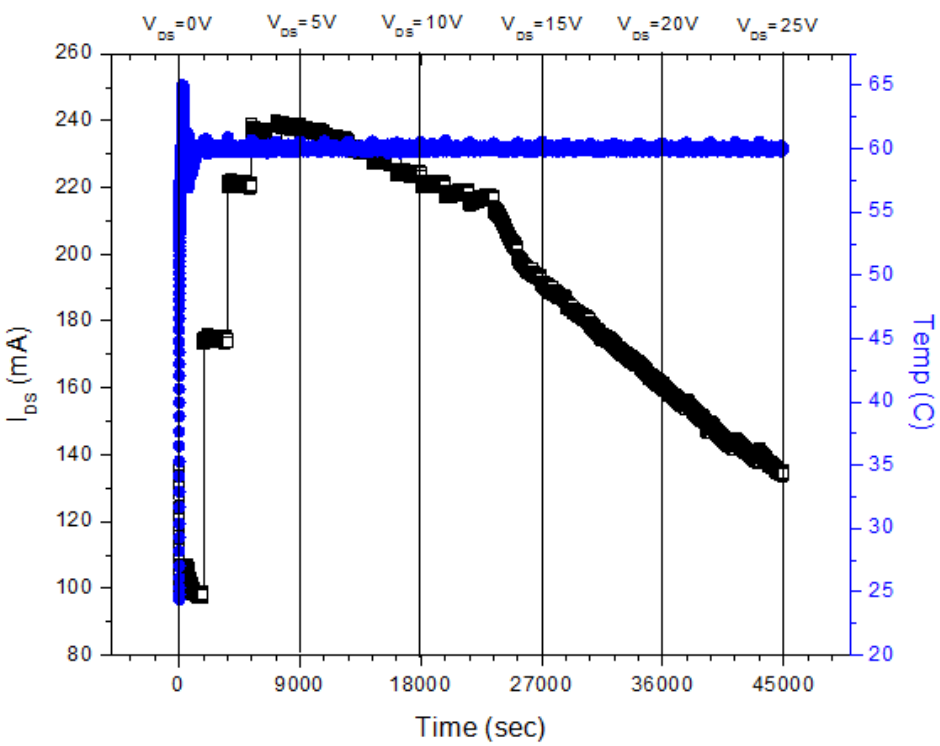


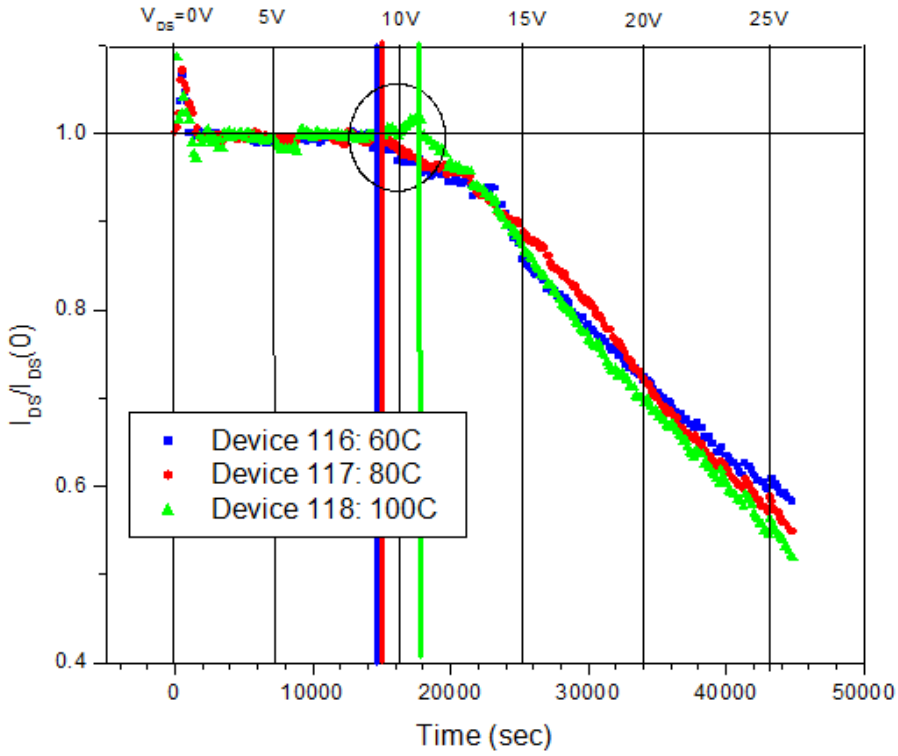
T=60°C
ΔRs=1.31Ω
ΔRd=14.69Ω
ΔVt=0.54V

T=80°C
ΔRs=0.56Ω
ΔRd=18.7Ω
ΔVt=0.5V

T=100°C
ΔRs=0.72Ω
ΔRd=20.14Ω
ΔVt=0.72V

ON-State Stress: HEMT





I_{DS} vs. time for step stress with T=60°C

I_{DMax} / I_{DMax} (0)
Degradation begins ~9-11V

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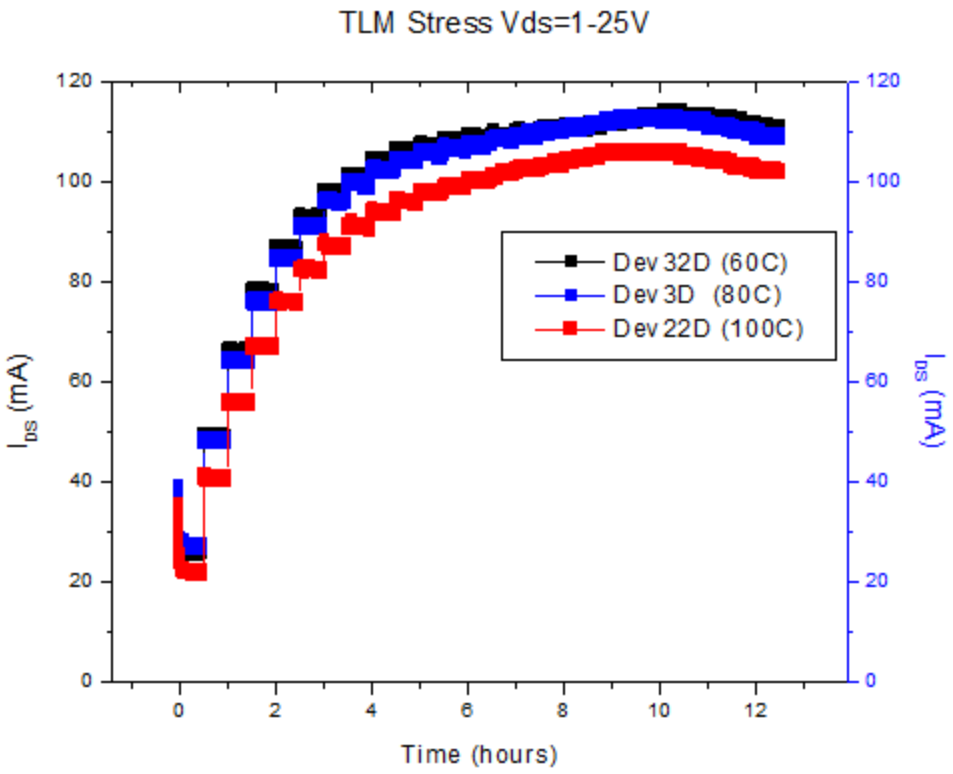
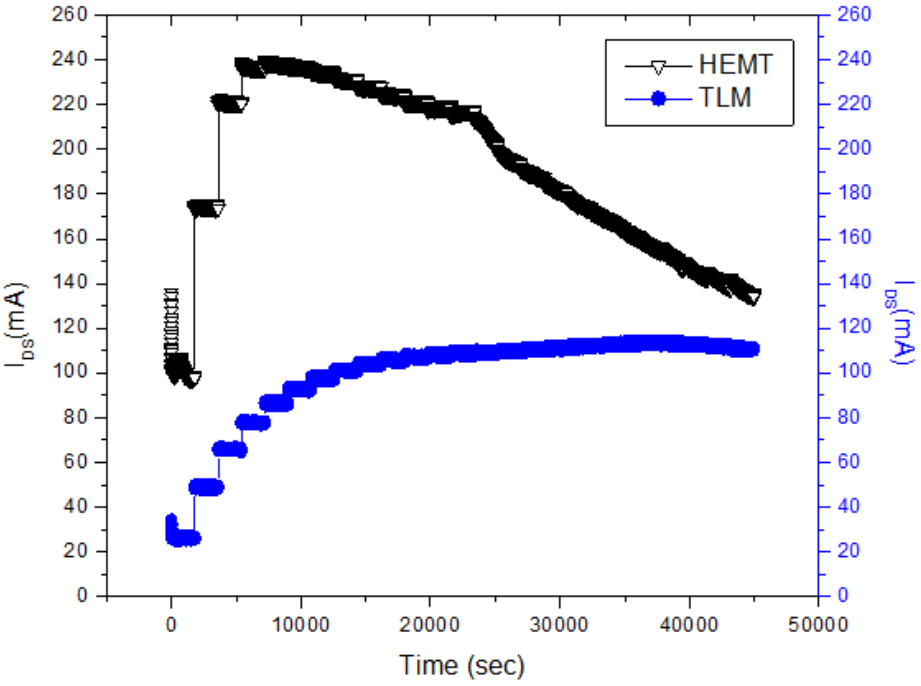
ON-State Stress: TLM

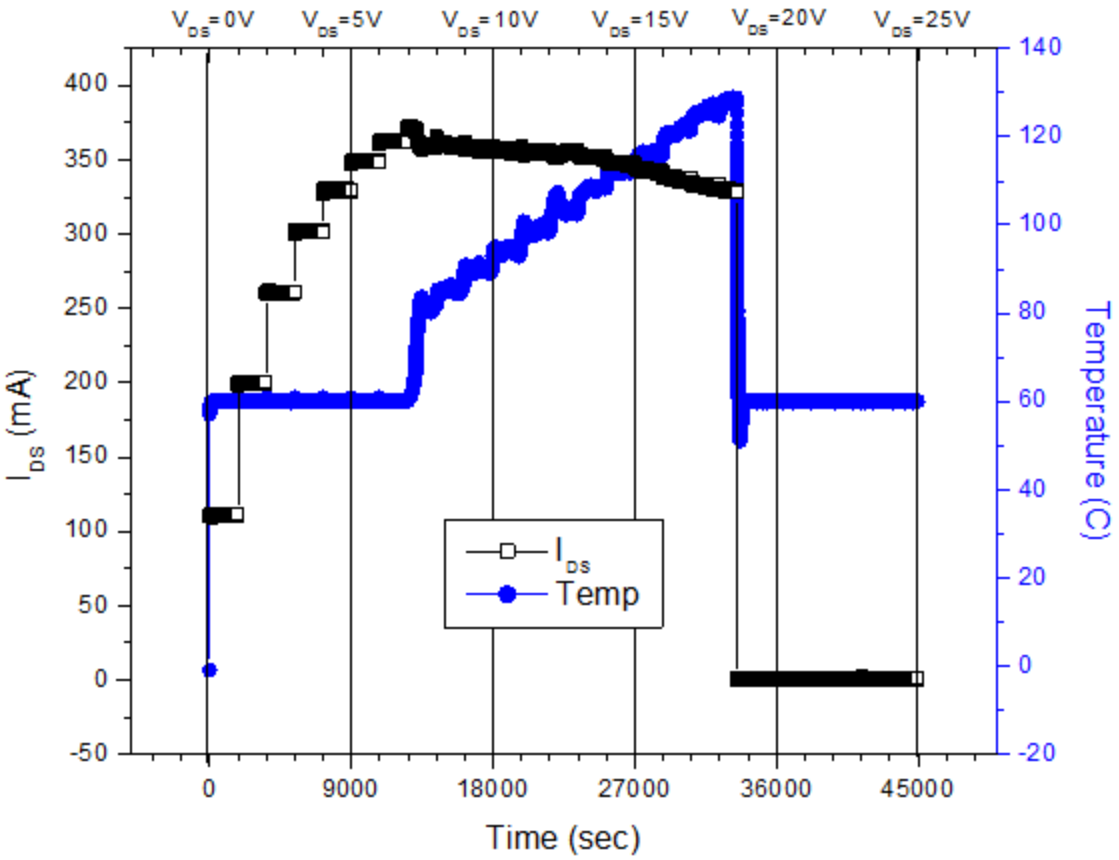


Current during stress at 60°C, 80°C, & 100°C



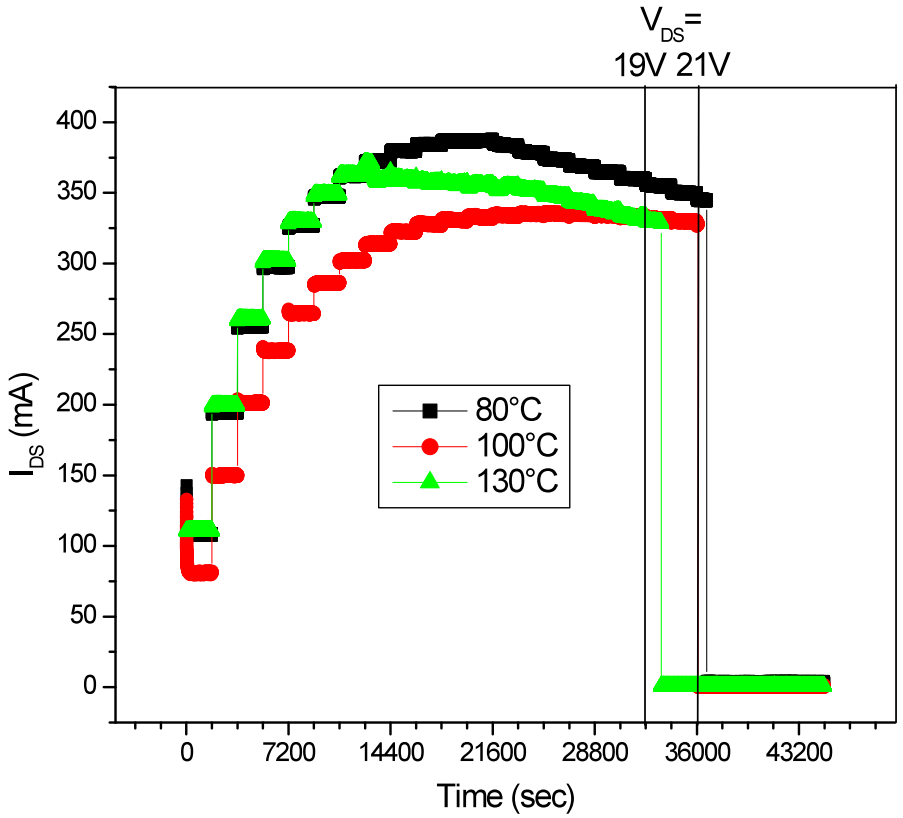
Step stress I_{DS} of device compared to TLM

High Power Stress: Gateless

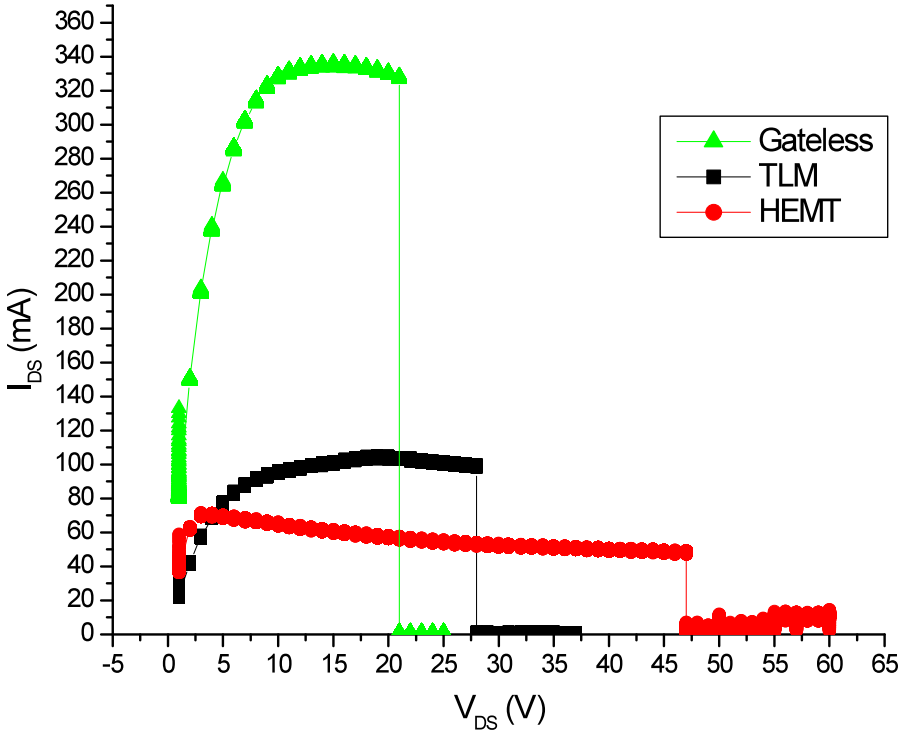


Peltier failed to regulate temperature of package, ultimately resulting in catastrophic failure of device

ON-State Stress



Gateless



Baseplate Temperature=100°C

Maximum channel temperatures: HEMT 110°C, TLM 162°C, Gateless 307°C

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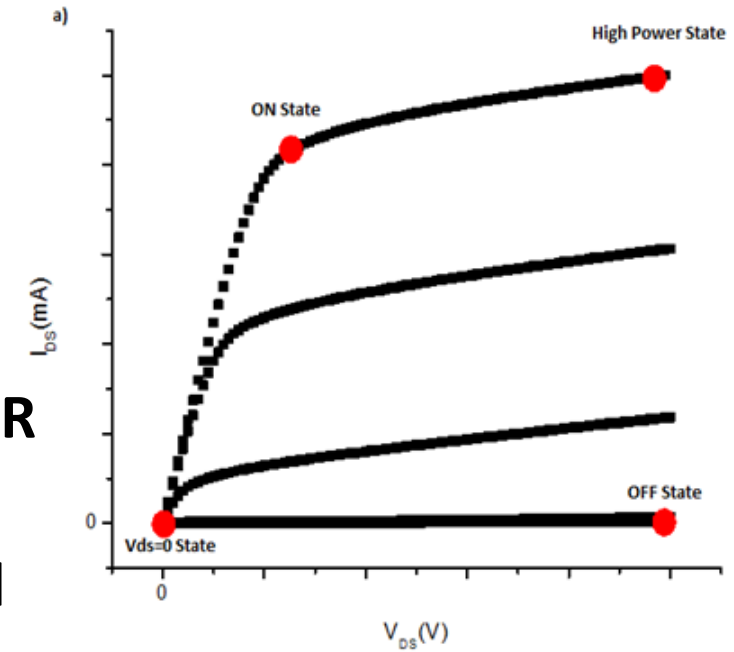
Cryogenic ON-State Stress

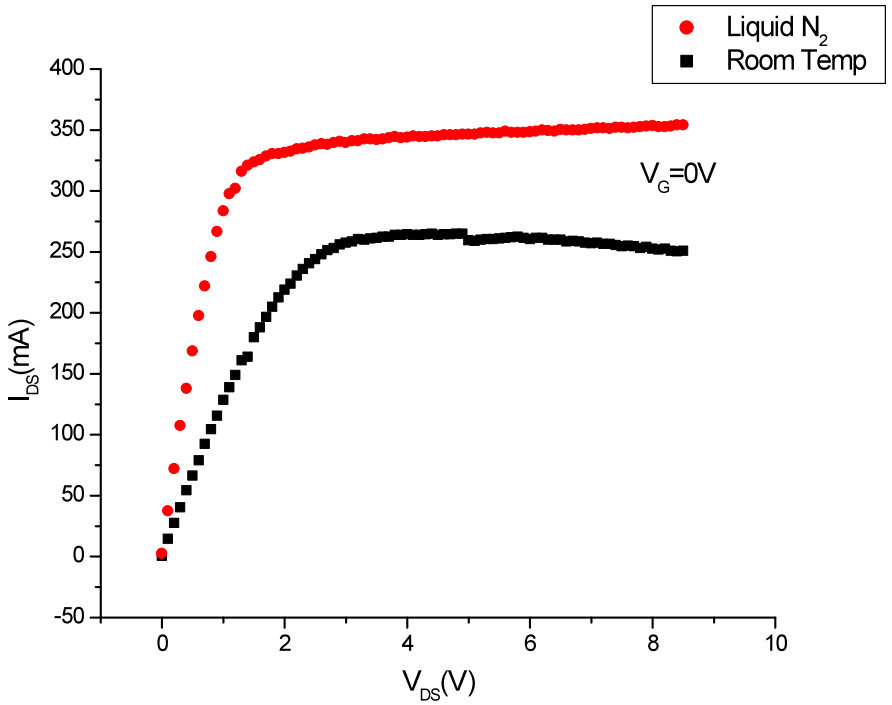
- Isolate temperature effect from hot electron stress (high power state)
- Submerge in liquid nitrogen
- Current increases at lower temperature

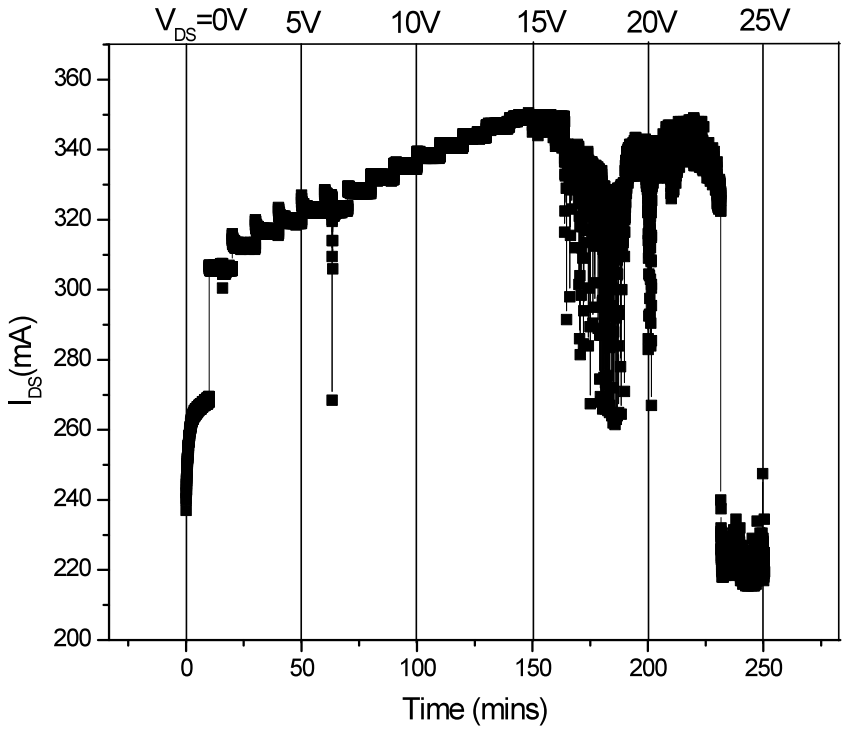
→ BRIDGES GAP BETWEEN **HIGH POWER** AND **ON STATE**

Ability to stress at higher current and lower electric fields than in high power state, and higher electric fields than ON state



Preliminary: Cryogenic Stress





~40% increase in I_{DSS}

Rapid LN_2 boil after 15V (~16W/mm). Permanent degradation after 24V applied (or ~25W/mm).
Field driven?

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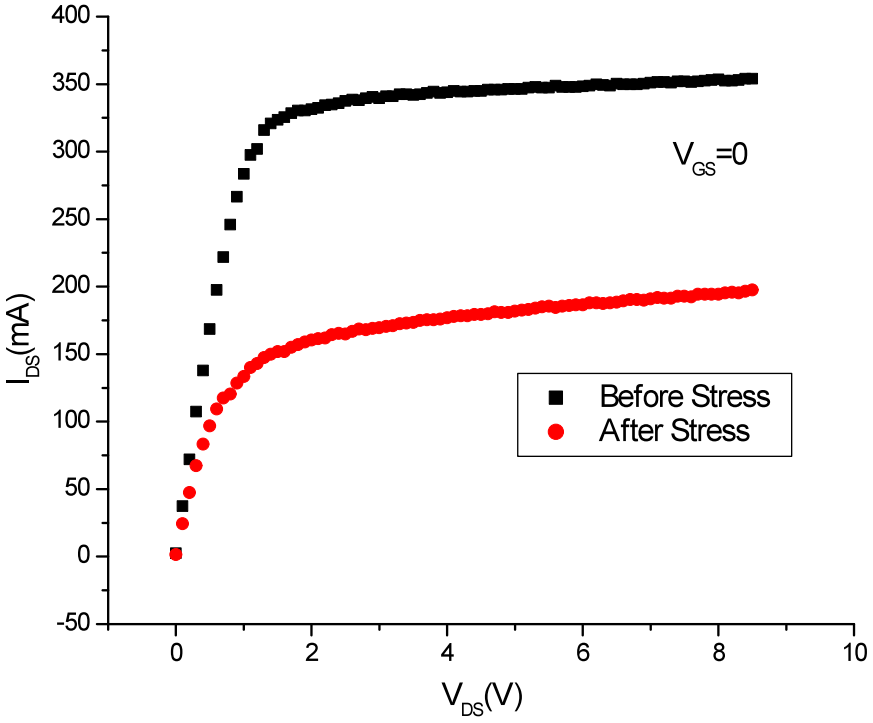
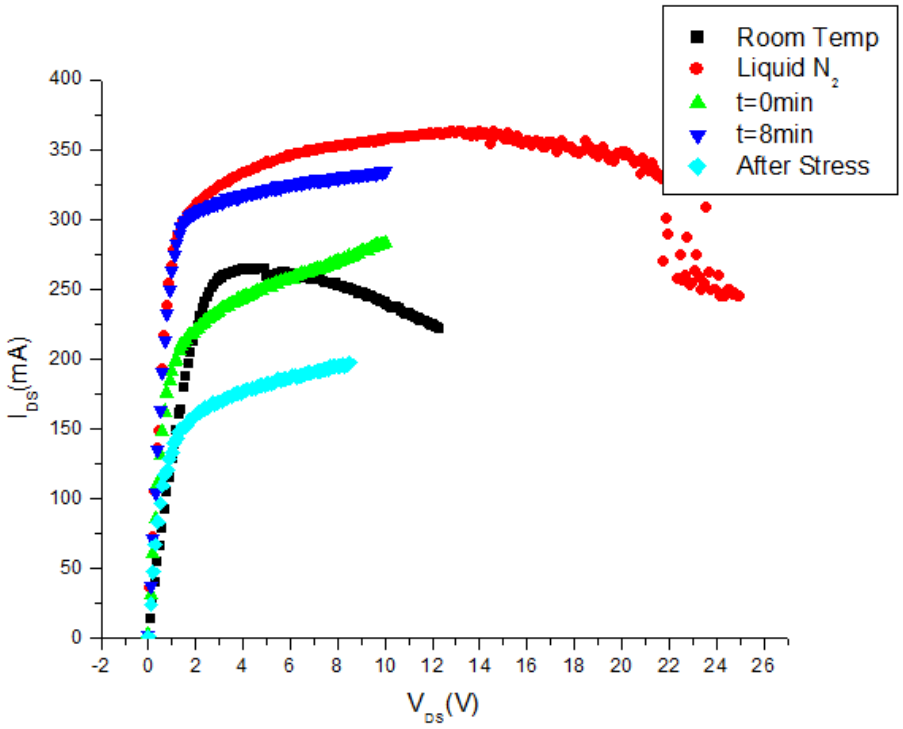
Cryogenic Stress





~45% permanent decrease in I_{DSS}

I-V sweep shows voltage breakdown at ~23V. Almost fully recovers.

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Outline

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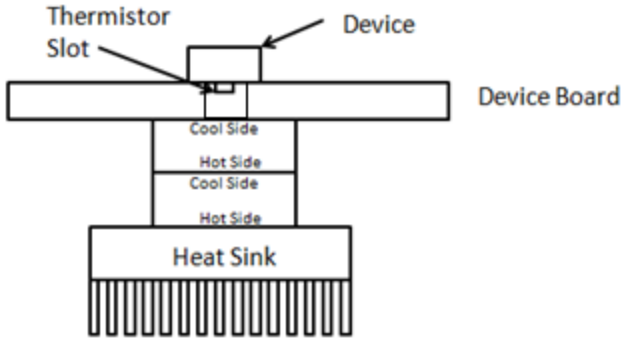
- **Thermal Simulations**
- Off-State Stress
- Conclusion

Steady-State Condition:

$$-k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=P_D$$



Where k is the thermal conductivity (W/m-K) and P_D is the source of power.

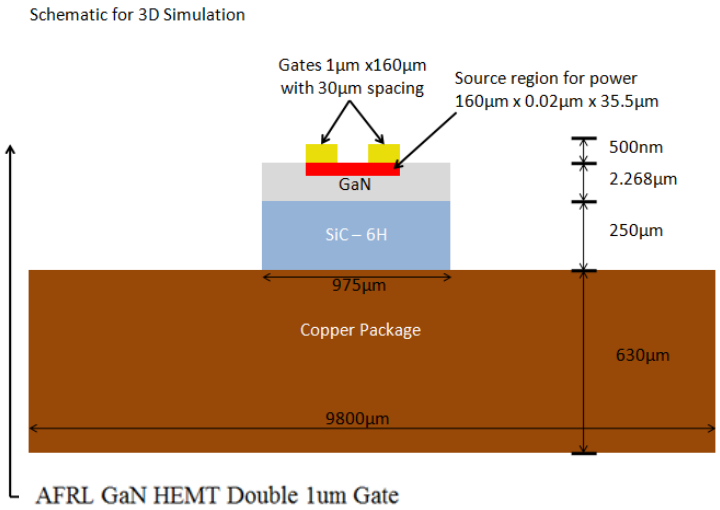
All boundary conditions are free convection except for the base-plate temperature of the package.

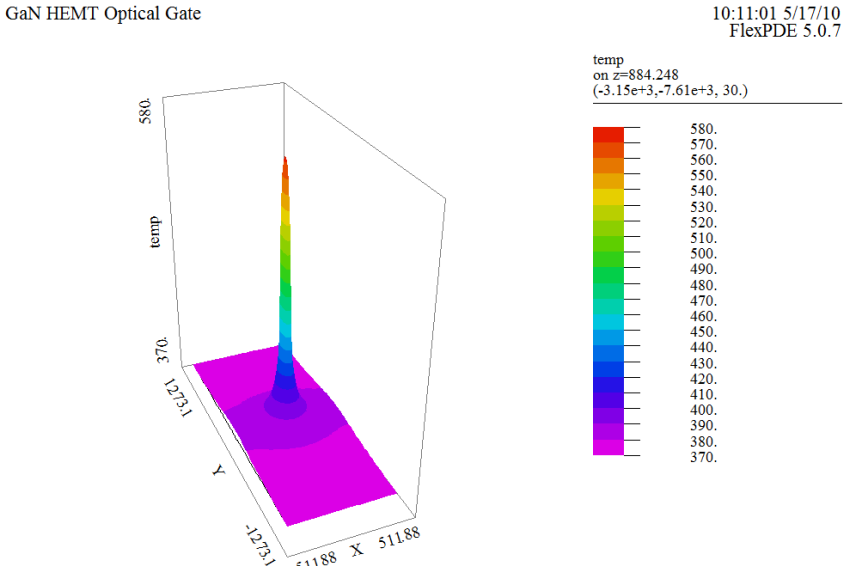
Temperature dependent thermal conductivity was employed in the simulation

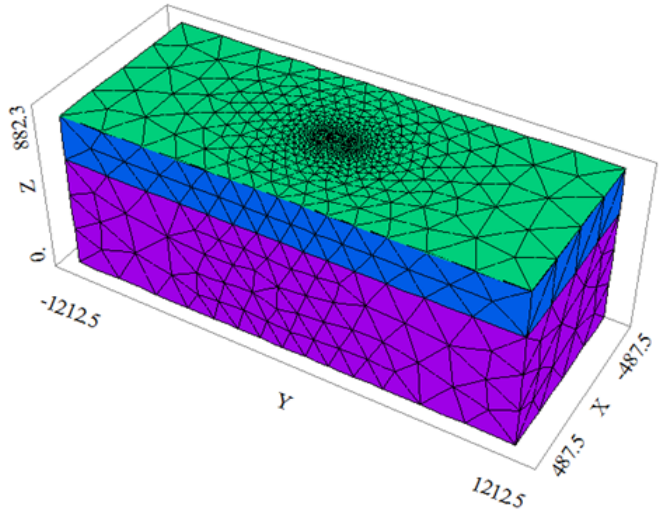
Material parameters: (from Bertoluzza et al. Microelectronics Reliability 49, 468 (2009).)

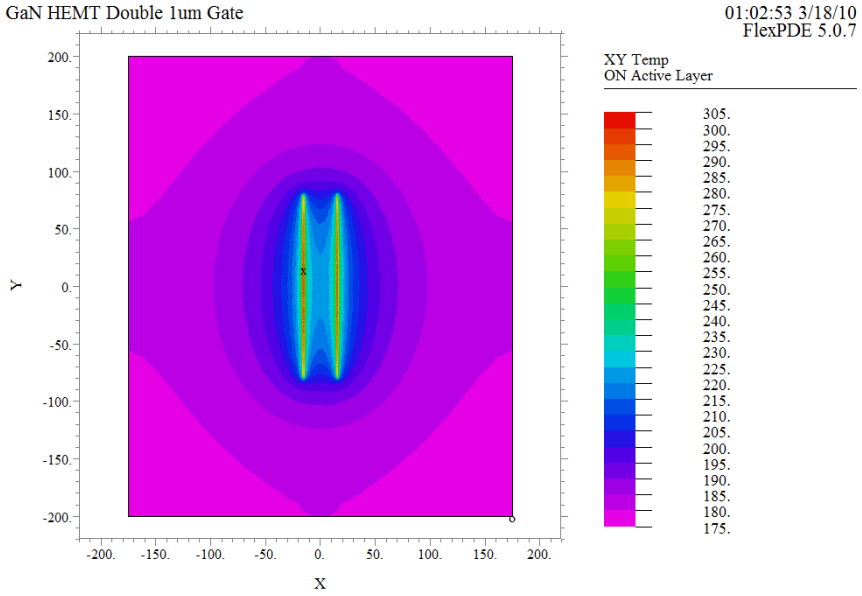
Material	Thermal Conductivity (W/m-K)
Sapphire	35*(300/T)
SiC	400*(300/T)
Si	$148*(300/T)^{1.3}$
GaN	$160*(300/T)^{1.4}$

Thermal Simulations



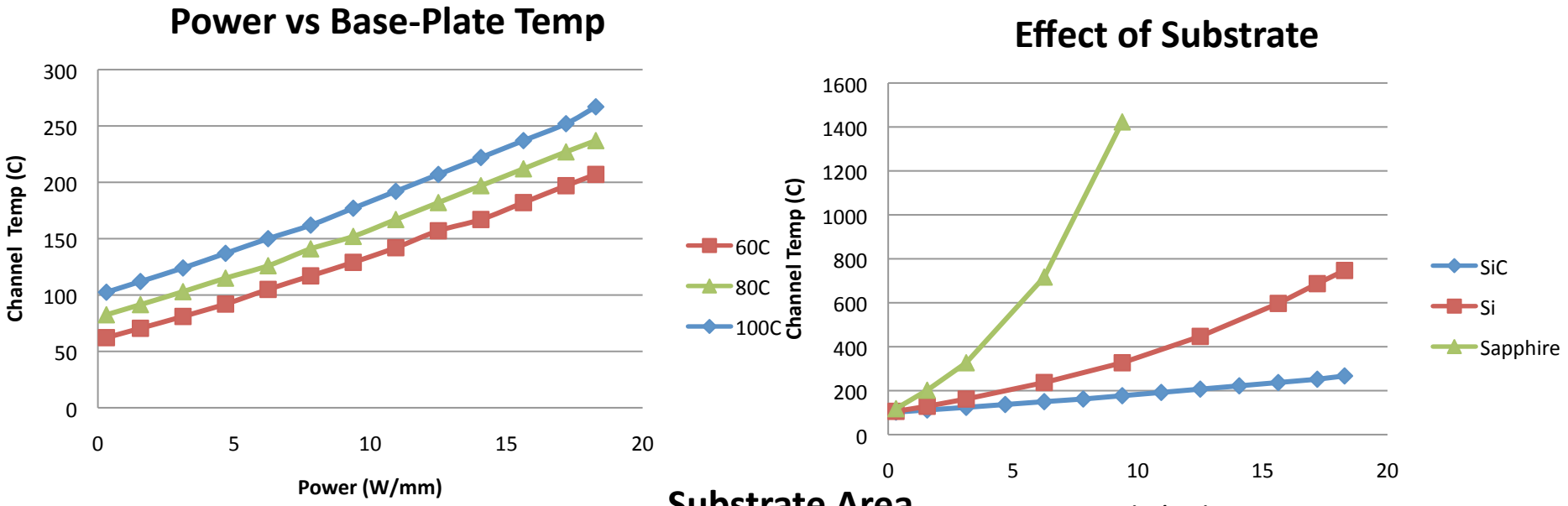


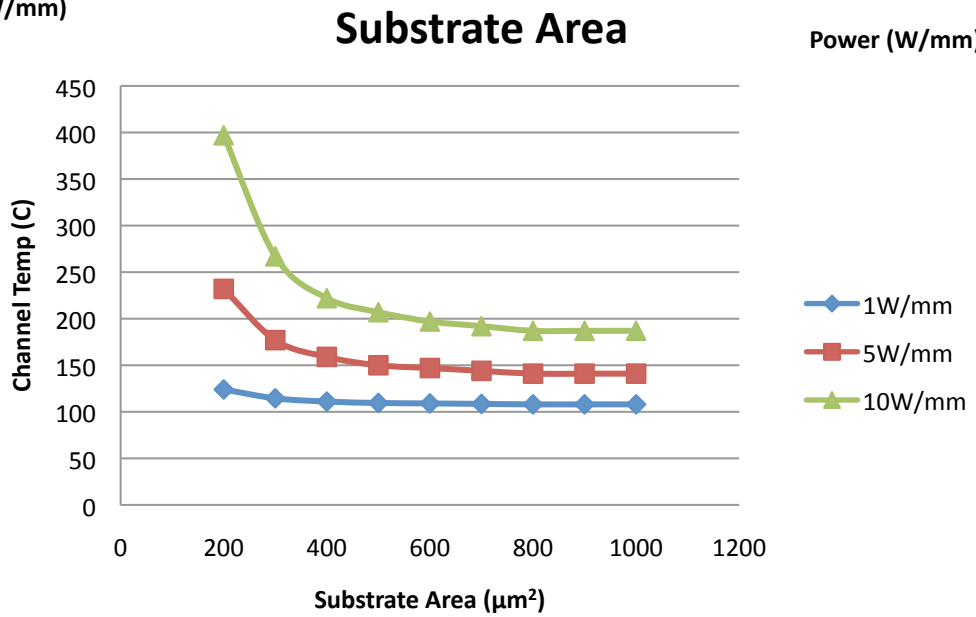




AFRL GaN Simulation v10: Grid#1 p2 Nodes=55414 Cells=36712 RMS Err= 1.8e-4
Surf_Integral= 4629728.

Simulations





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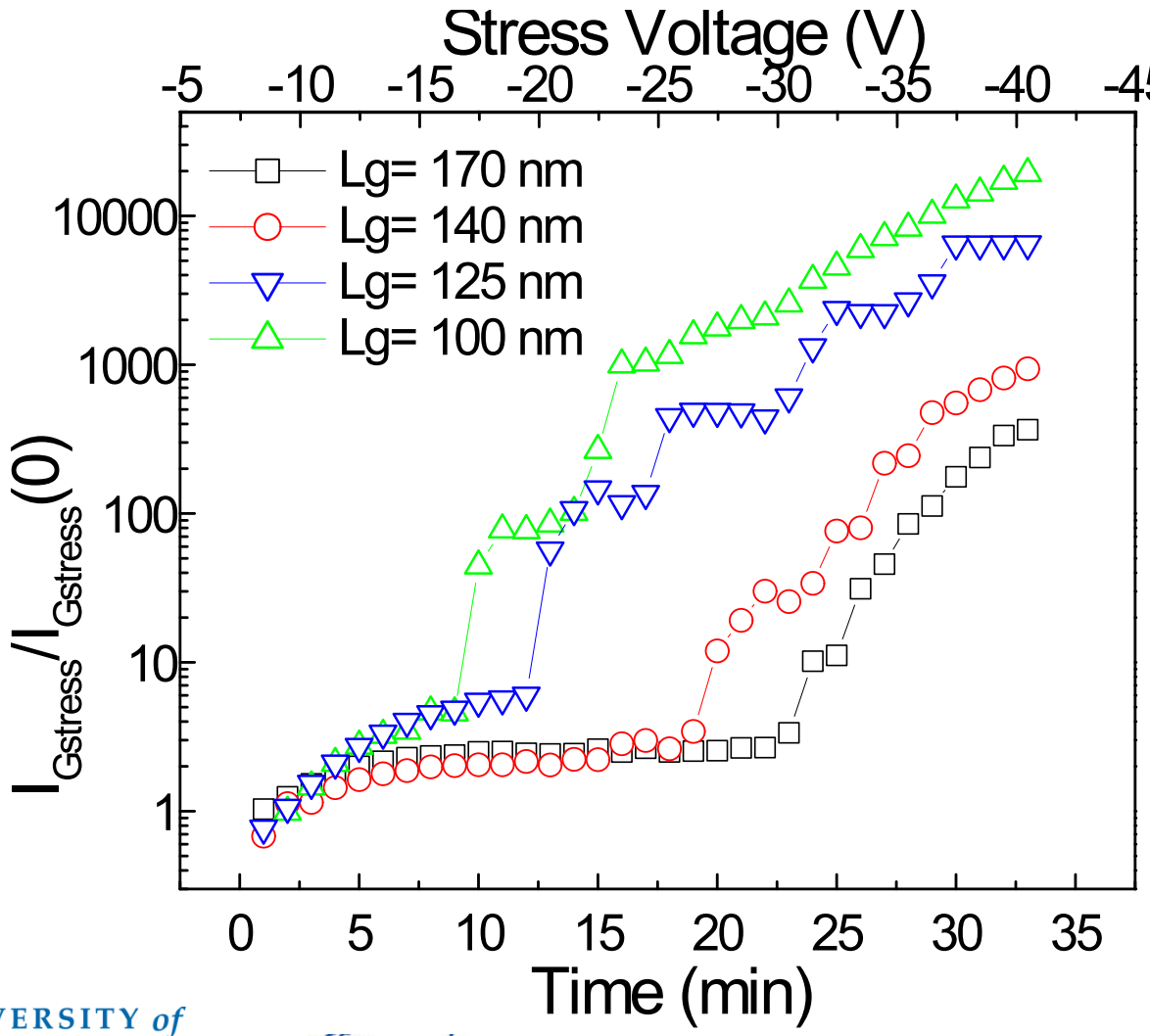
OFF-State Stress Conditions

I. V_{GS} step biased from -5V to -42V in -1 V step while V_{DS}= 0V; Source and drain grounded.

II. V_{GS} step stressed from -5V to -42V for different value of V_{DS}. V_{DS}= 0V, 1V, 5V, 10V and 15V.

III. V_{GS} step biased from -10V to -42V on device (100nm off-center gate)
   1. Ground source
   2. Ground drain

OFF-State Stress



V_{CRIT} = -17V (100nm)
V_{CRIT} = -22V (125nm)
V_{CRIT} = -27V (140nm)
V_{CRIT} = -32V (170nm)

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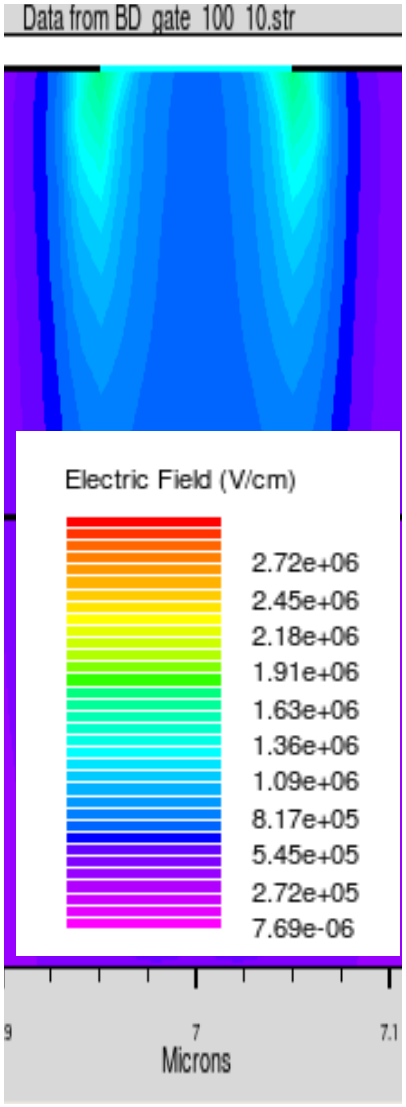
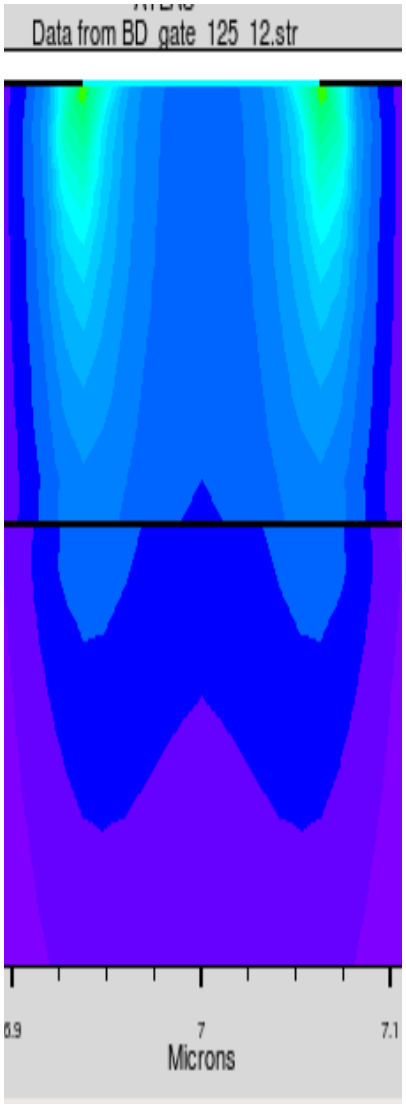
Electrical Simulations

2D simulation of gate degradation field for different gate length

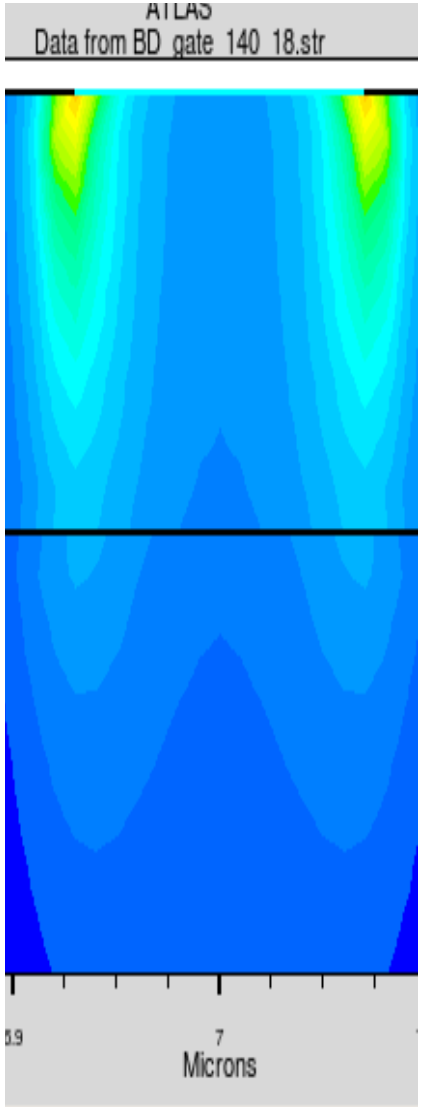
L_G = 100nm



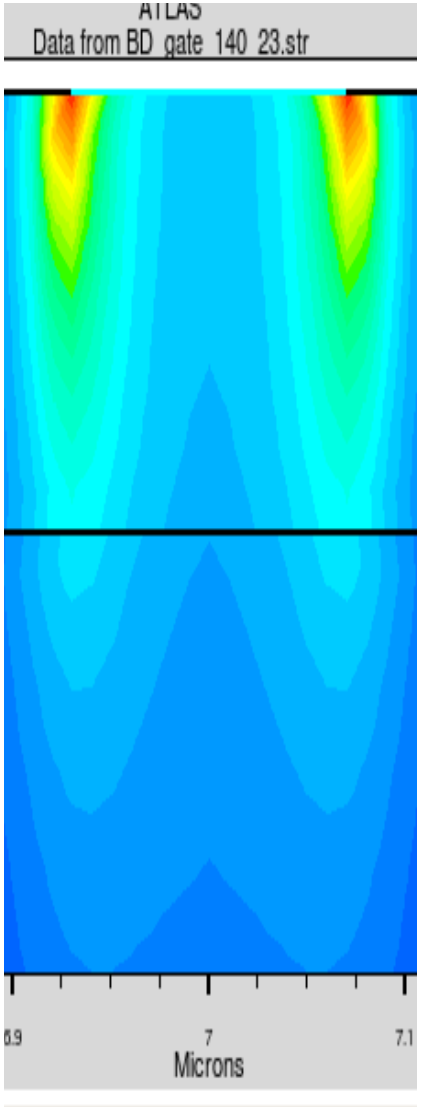
L_G = 125nm



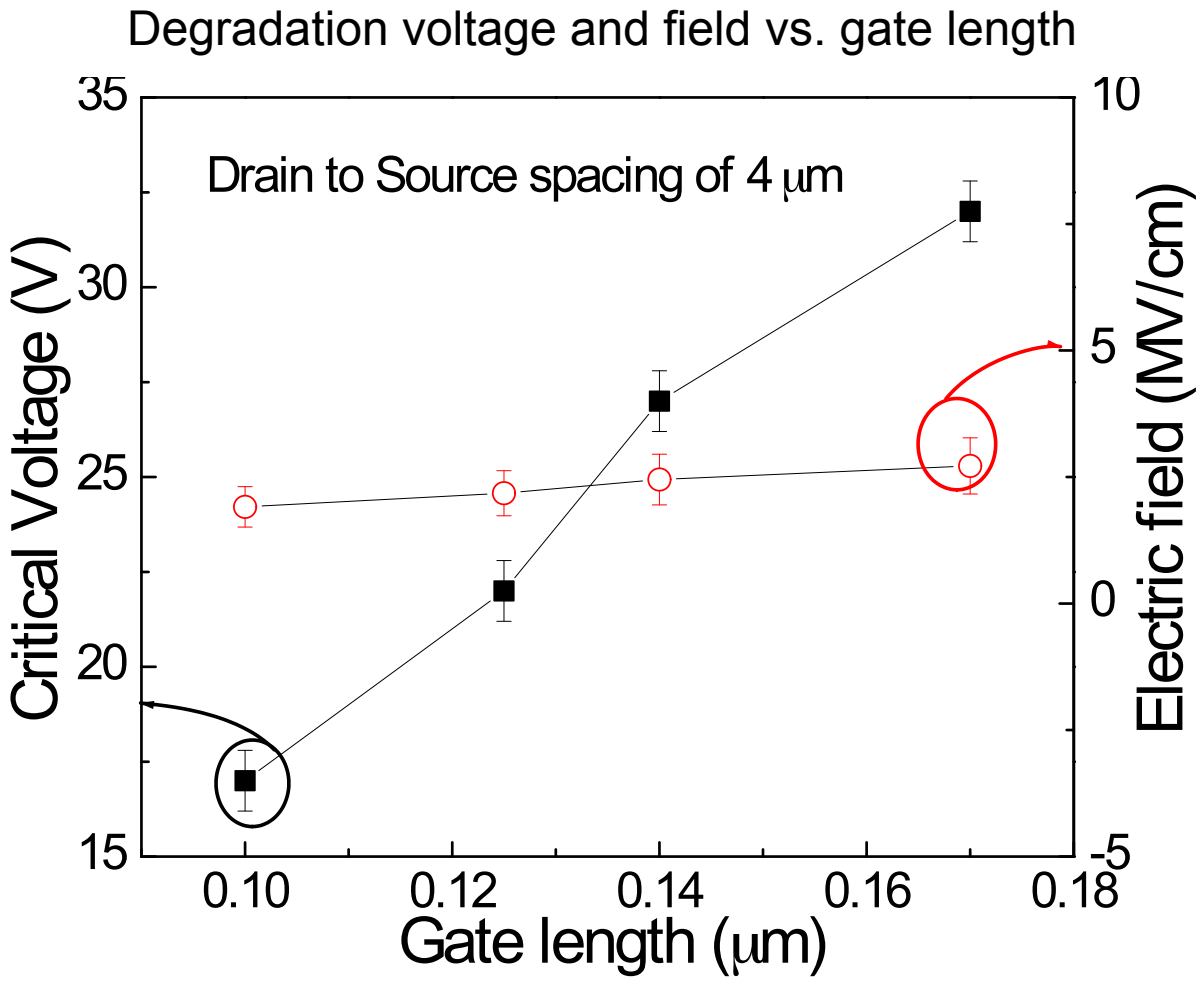
L_G = 140nm



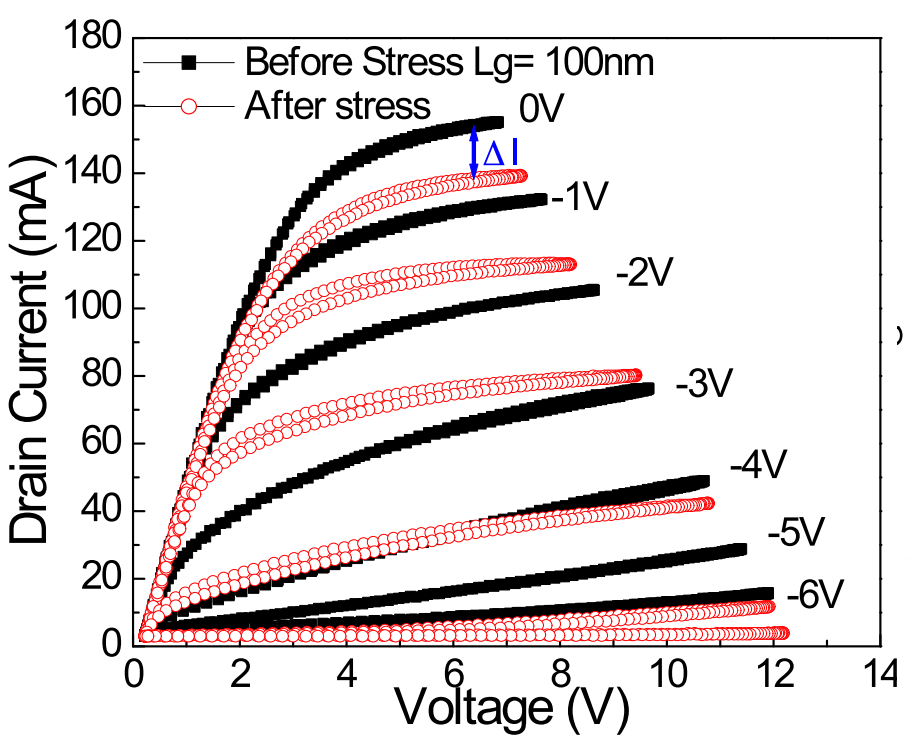
L_G = 170nm

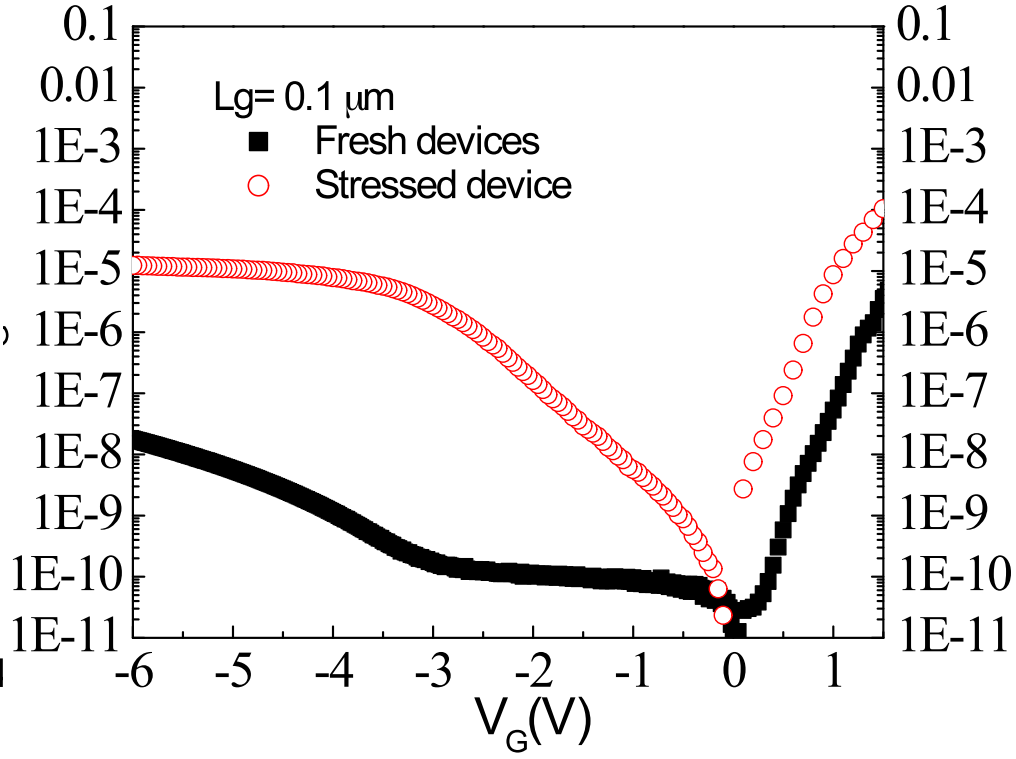


OFF-State Stress



OFF-State Stress





Drain current curves before and after DC stress

I_{GS}-V_{GS} plot before and after DC stress

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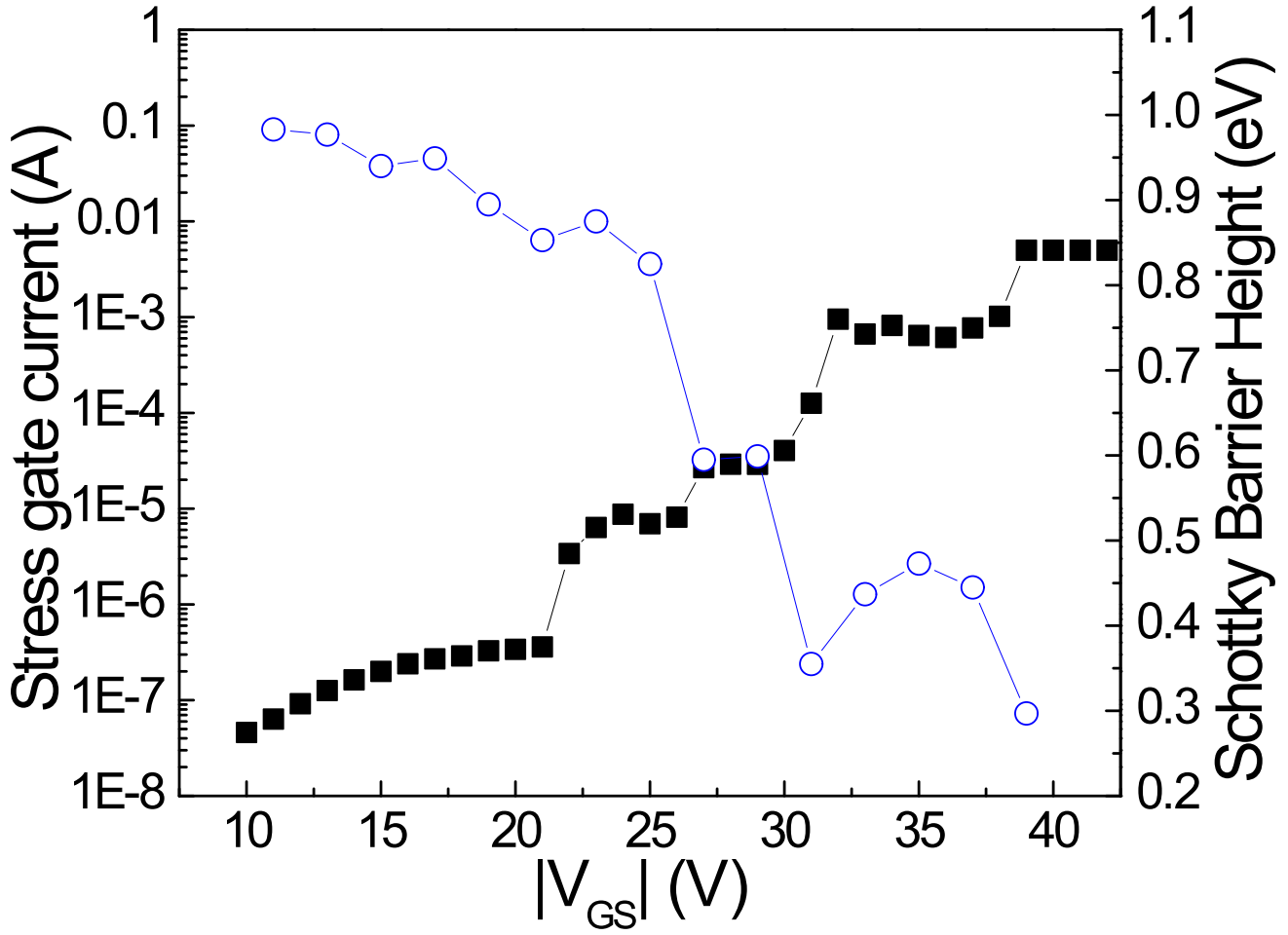
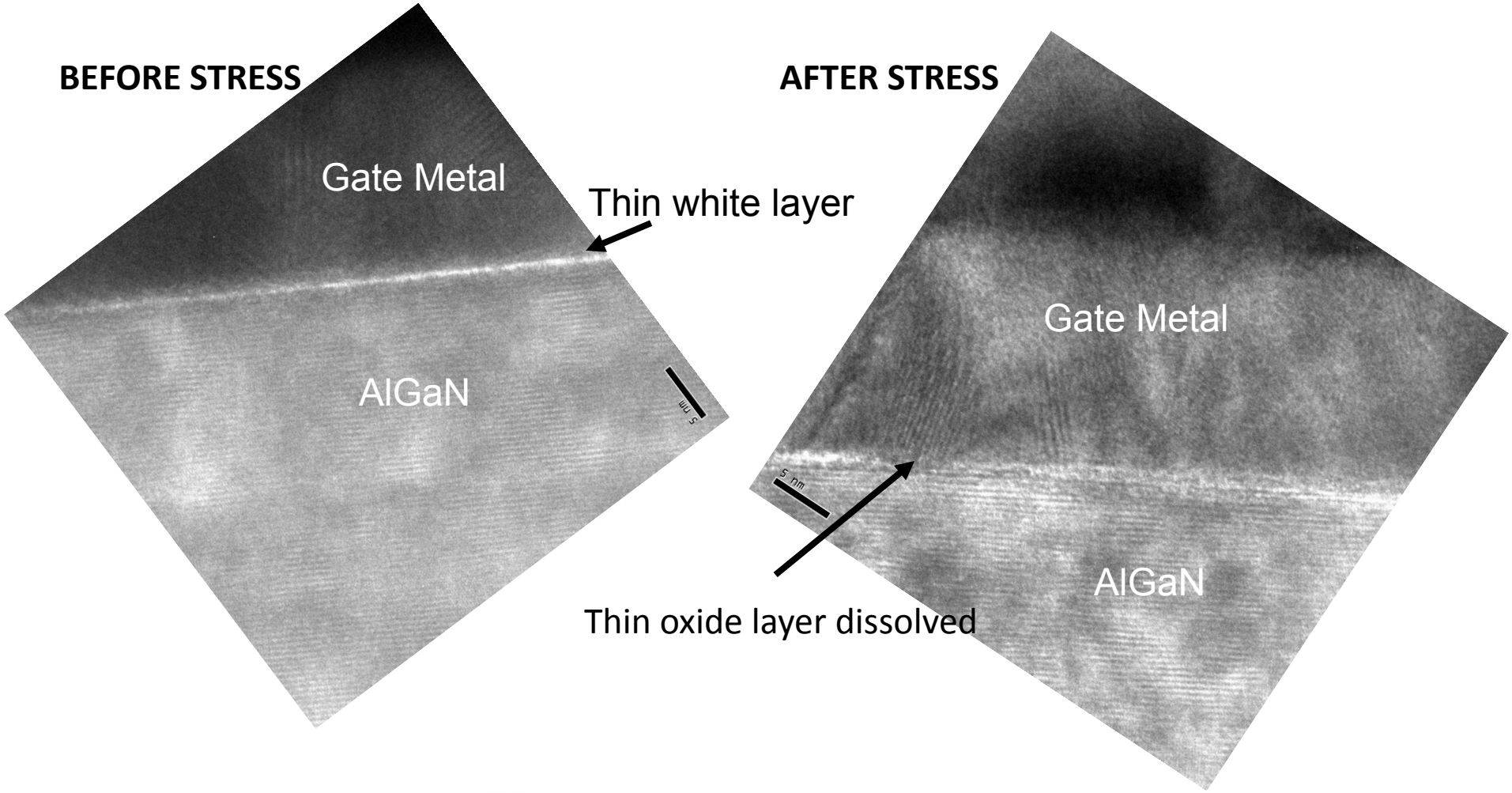
OFF-State Stress



OFF-State Stress



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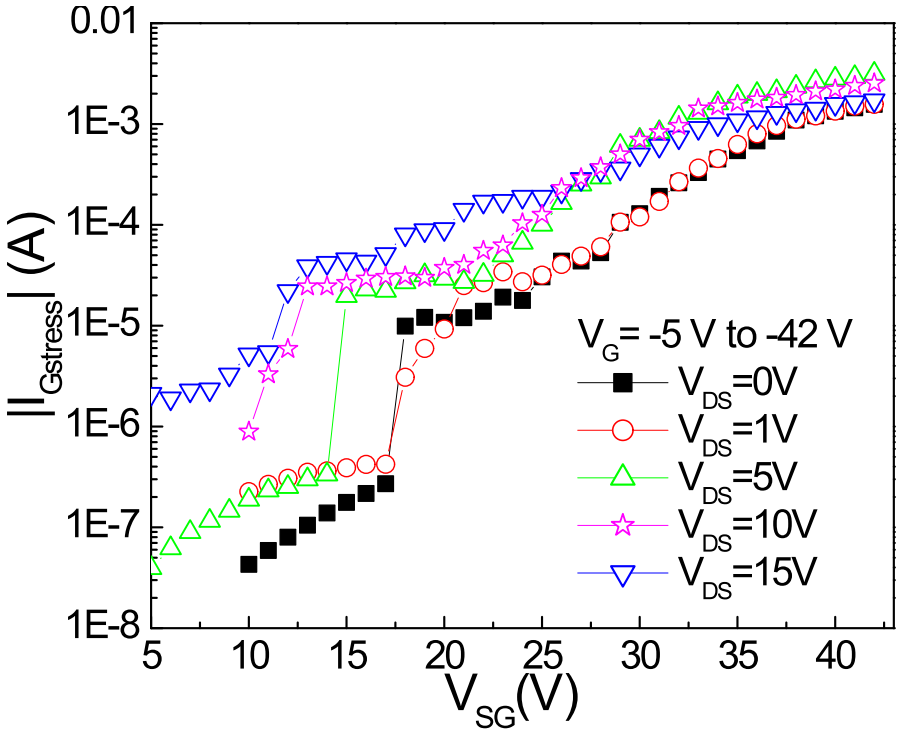
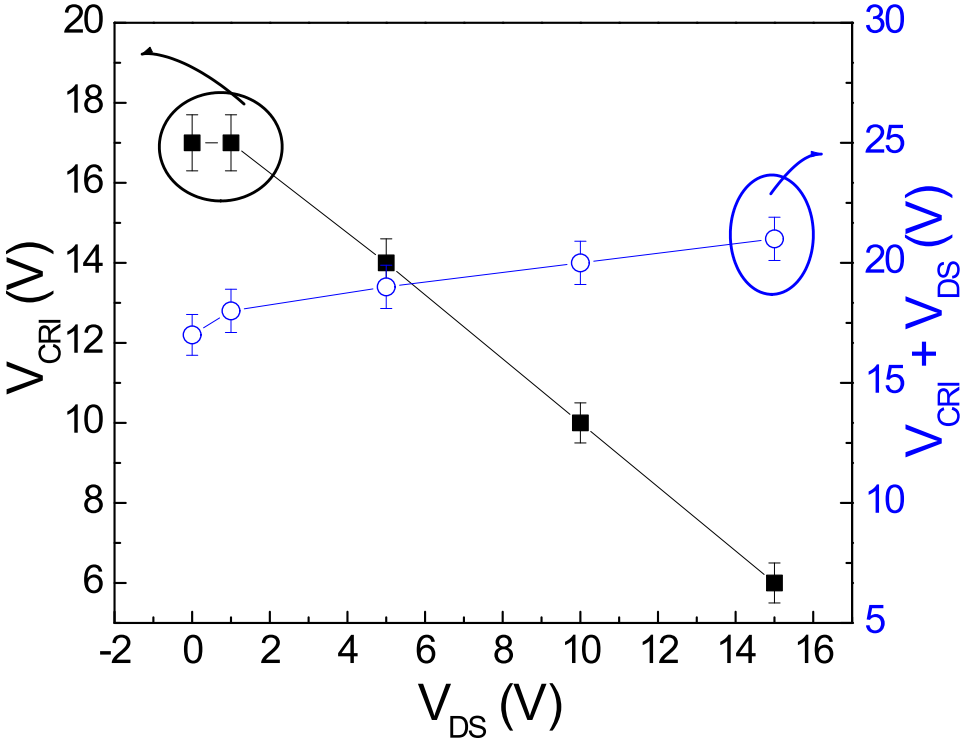
OFF-State: Drain Bias



Change in stress gate current in step-stress experiments for different values of V_{DS}.



(Critical voltage + applied drain voltage) as a function of applied drain voltage

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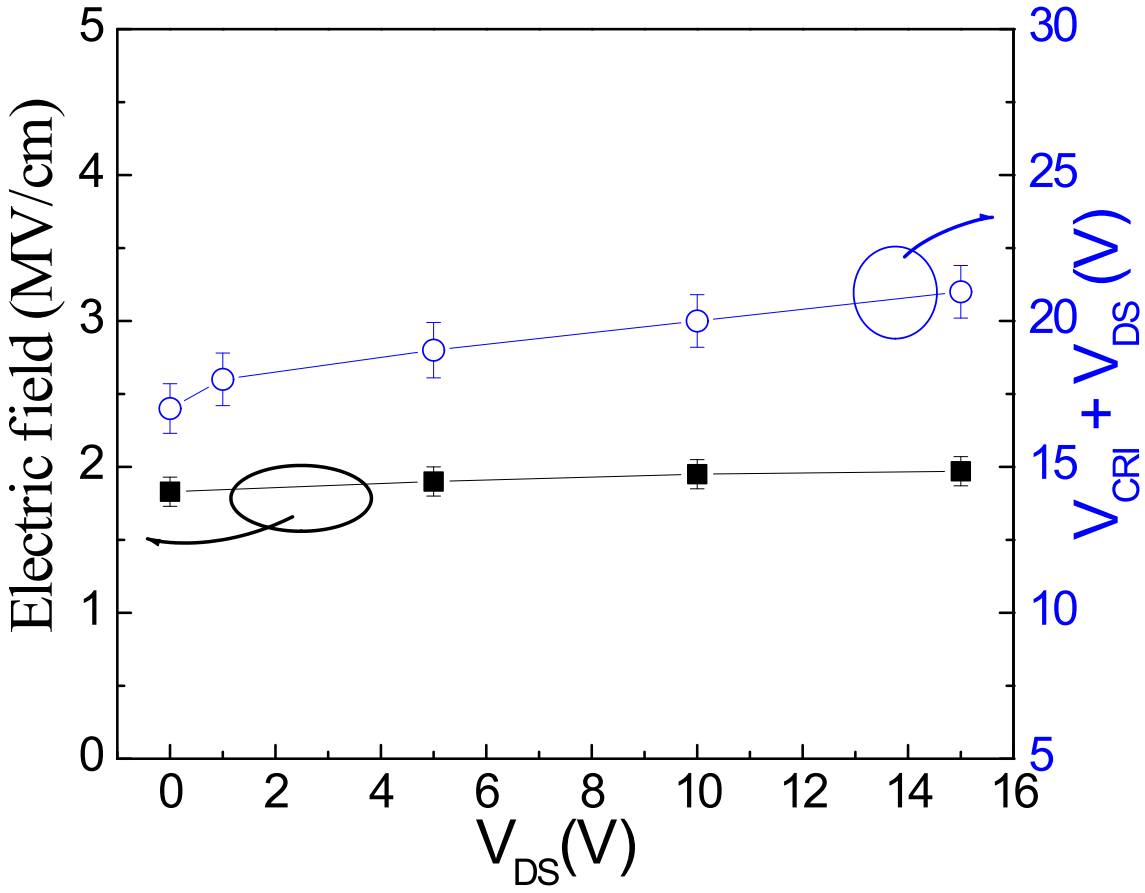
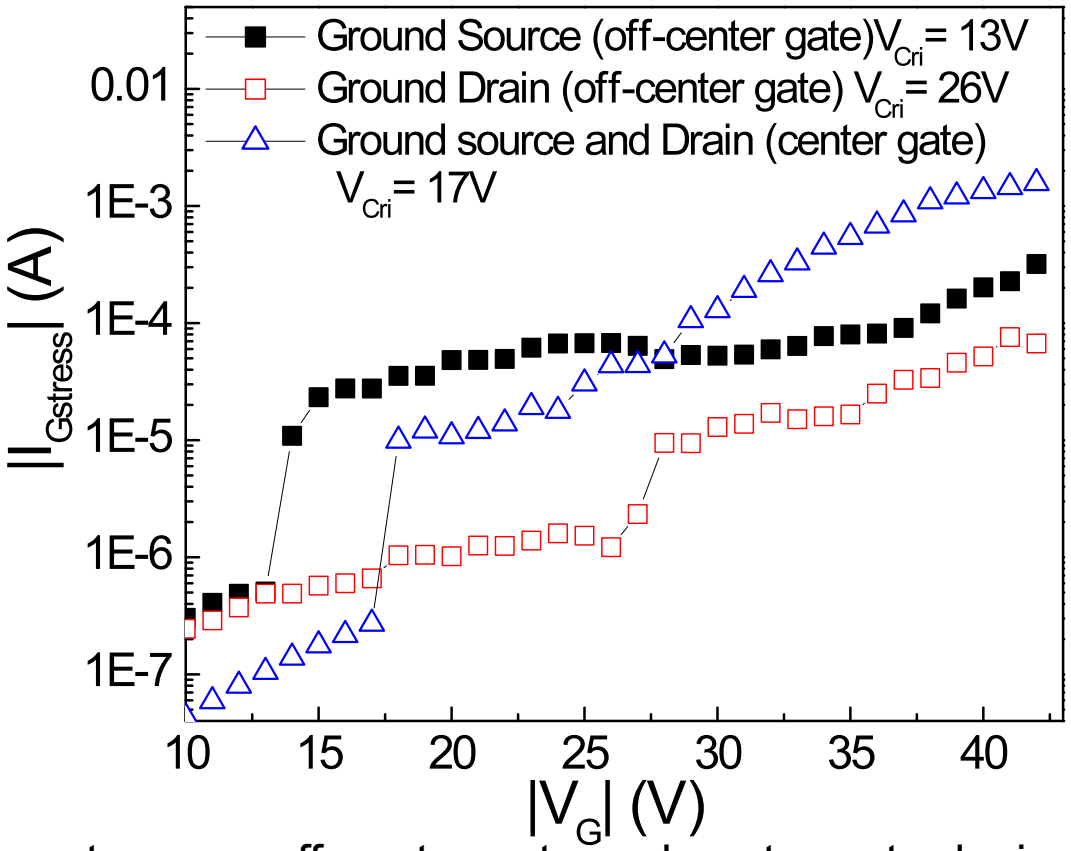
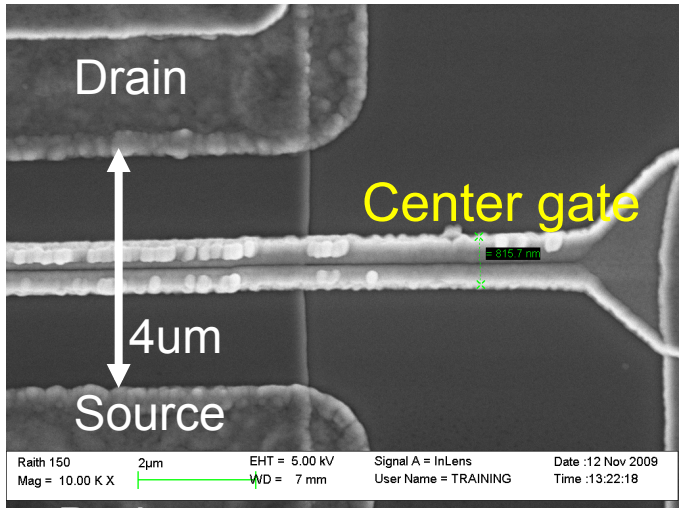
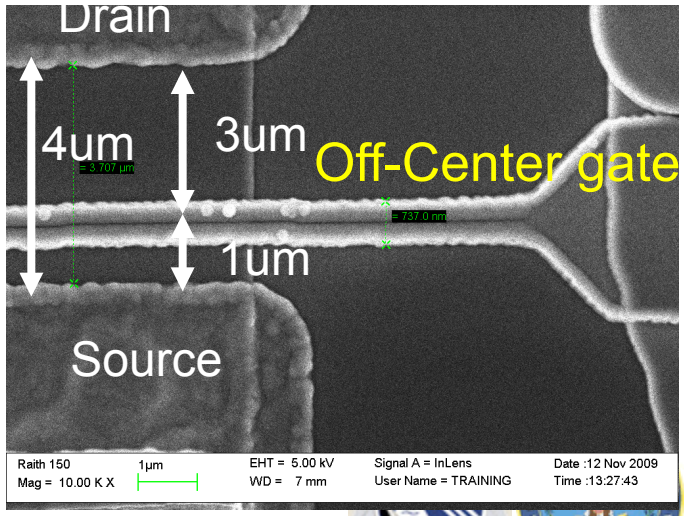


Degradation field as function of applied drain voltage

OFF-State Stress: Distance







Step-stress on off-center gate and center gate devices

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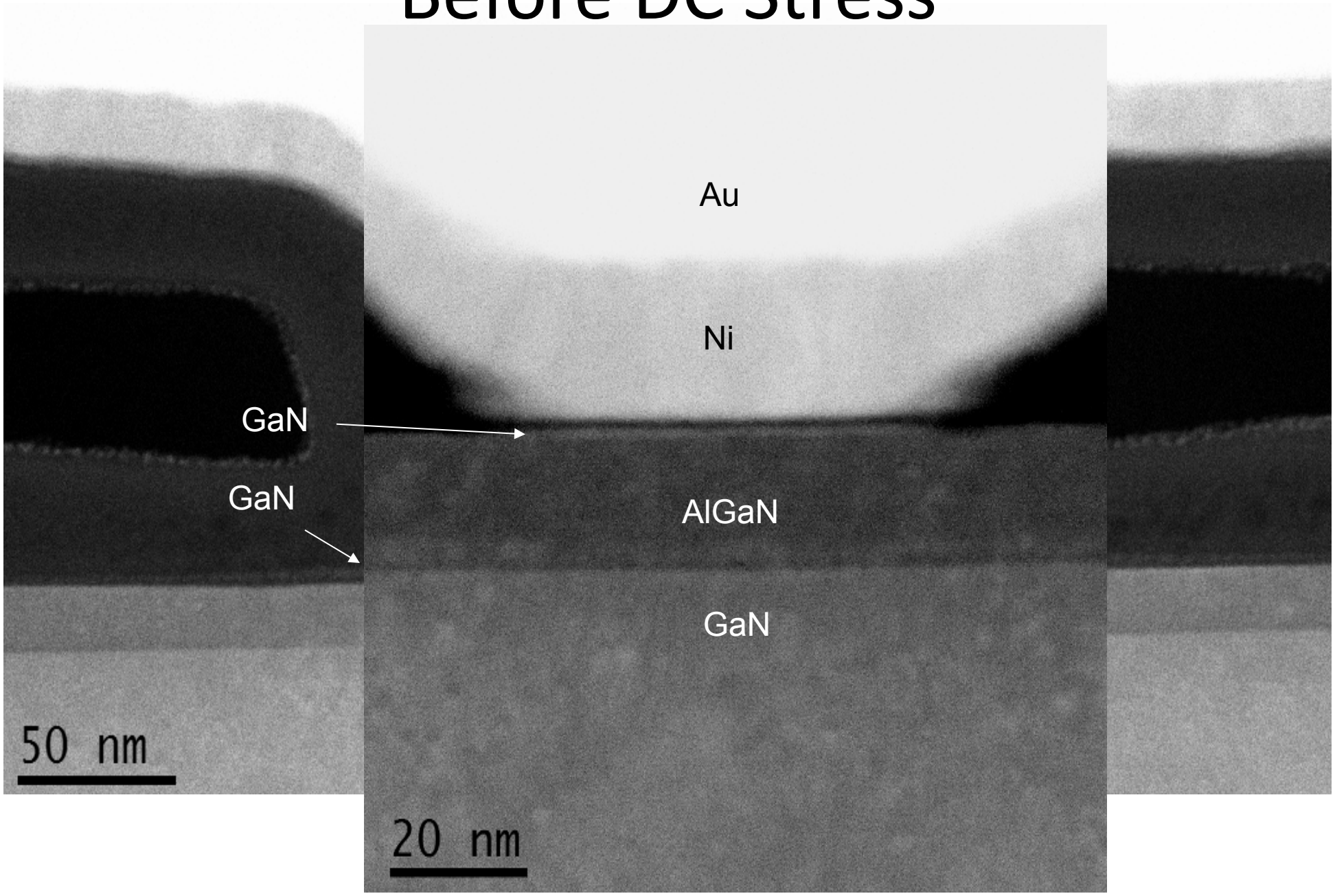
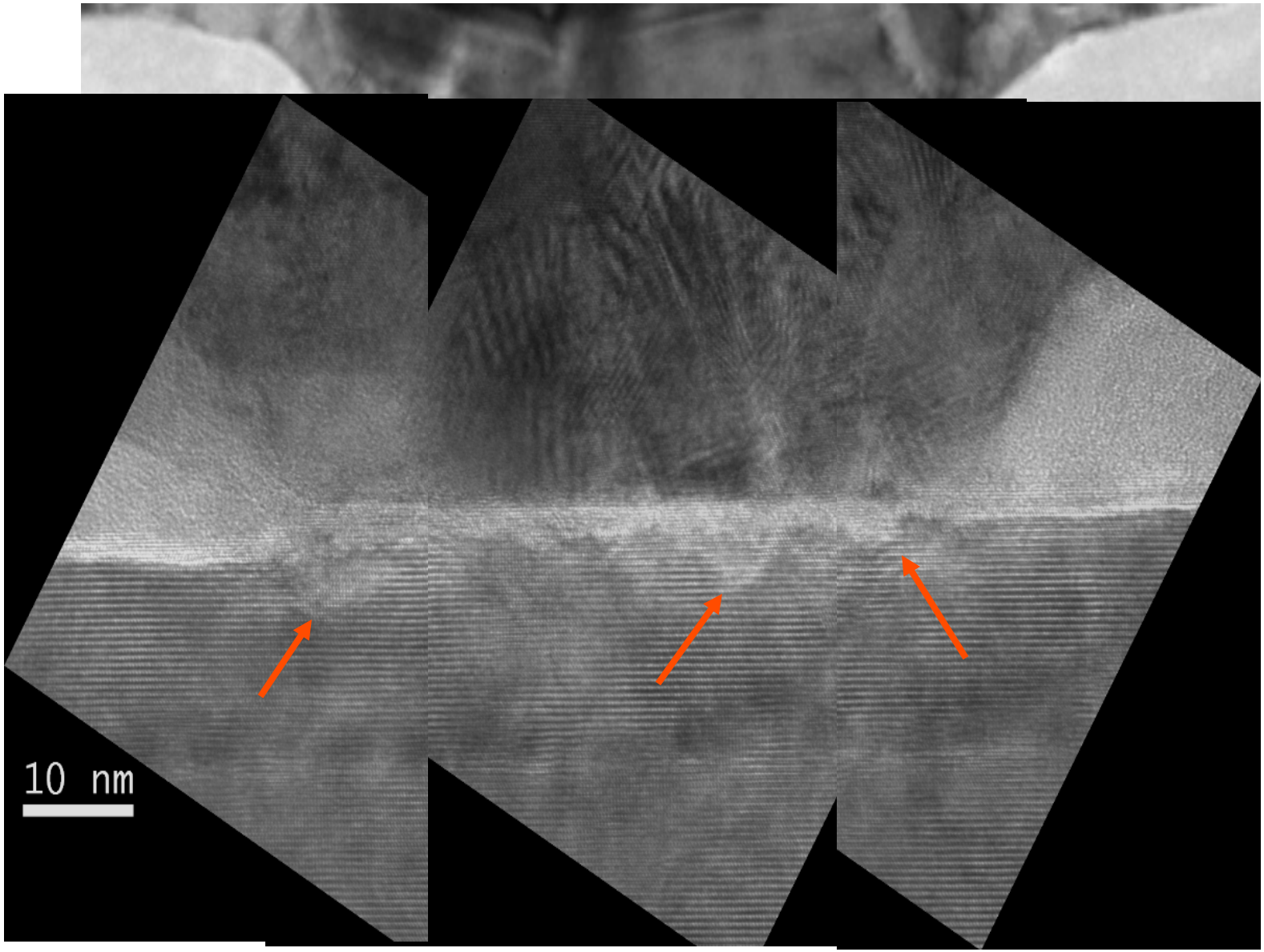
Before DC Stress

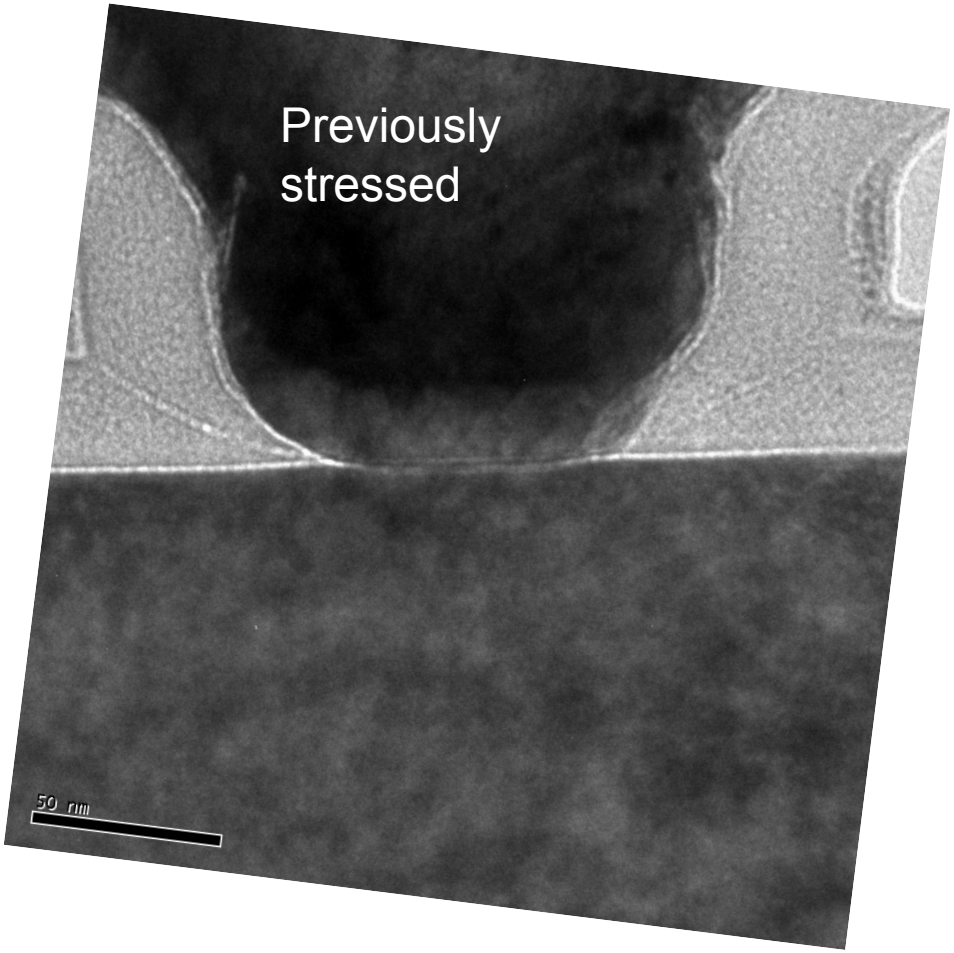


After DC Stress

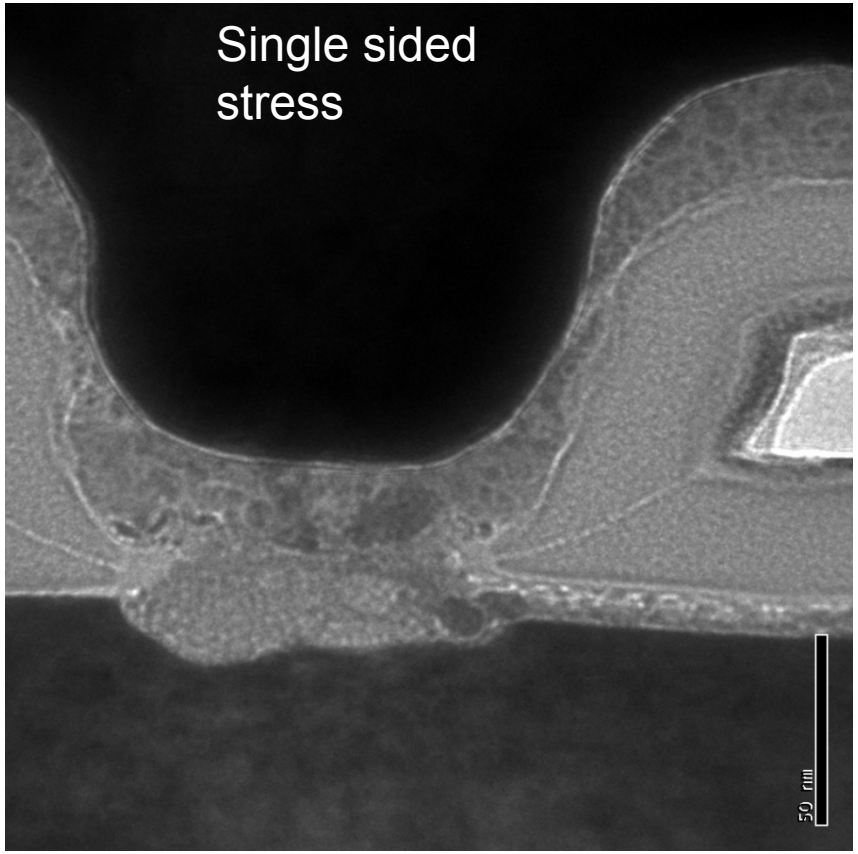


Comparison between stressed devices

V_G= -10 to -42V with -1V step.
Grounded source and drain



V_G = -10 to -42V with -1V step.
Grounded source and applied V_{DS}=10V



Conclusion

- AlGaN/GaN HEMT with 170nm gate length showed severe degradation after step stressing drain from 1V to 25V, where as TLM exhibited excellent stability.
- Increased baseplate and channel temperatures decreases voltage at which catastrophic failure occurs.
- Off-state stress showed linear relationship between critical degradation voltage and gate length
- Oxide layer is present between gate and GaN cap layer before stressing, but consumed after DC stress. Gate leakage current also increases after DC stress.
- Atlas simulations show constant electric field for breakdown at various critical voltages.